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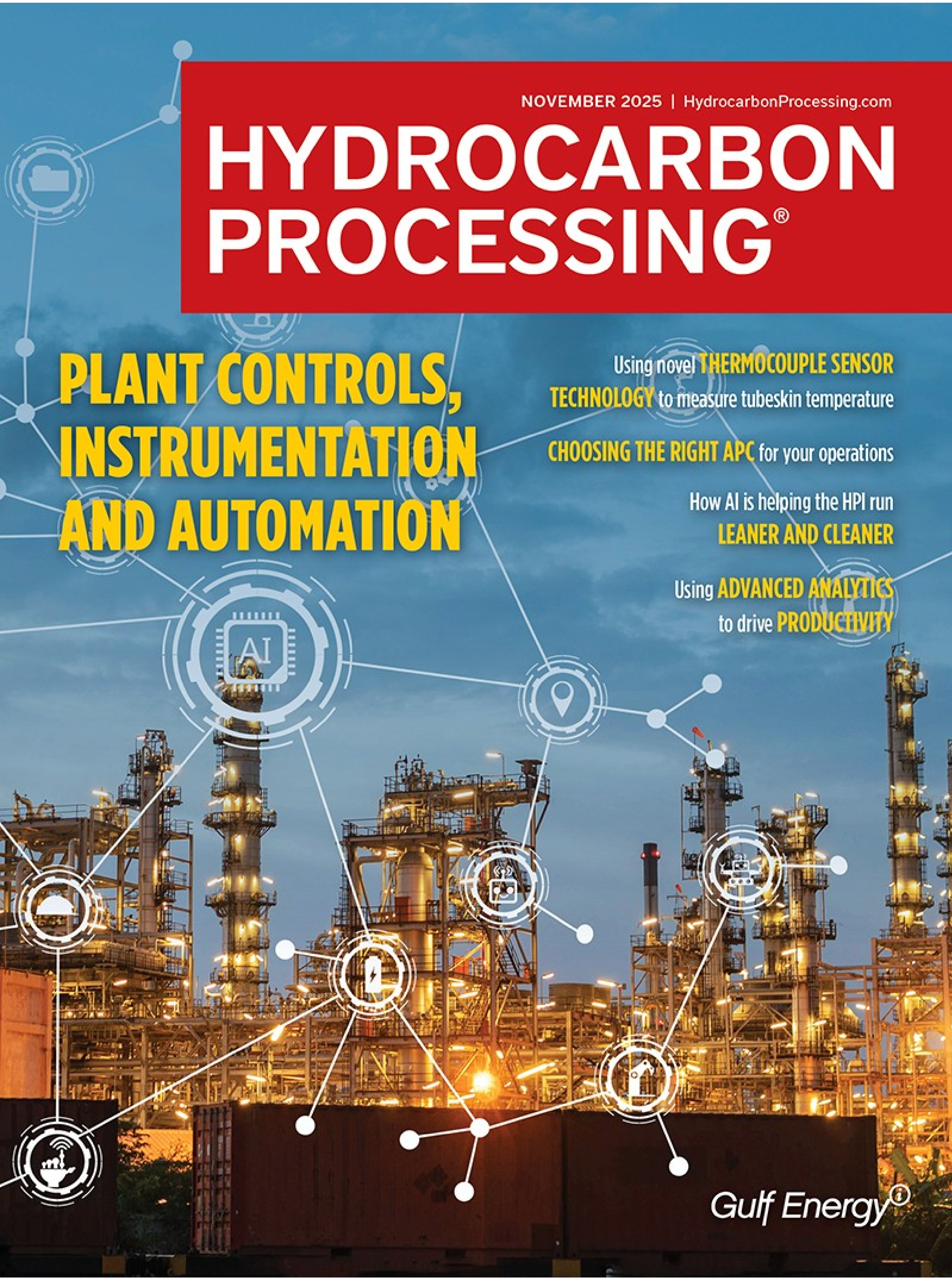

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Liquefaction MPC delivers holistic business returns

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Multivariable predictive control (MPC) technology has been successfully applied to many liquefied natural gas (LNG) processing plants around the world, but there are always challenges that must be overcome to achieve success. For the Queensland Curtis LNG (QCLNG) site, these challenges included addressing deficiencies in the base layer control strategies, managing the highly heat-integrated process design, modeling the various degrees of freedom into a net positive optimization strategy, and handling the dynamics of process disturbances such as ambient temperature and ship-loading on the operating point.

The MPC project team, comprised of the operating company and external specialists, used a proven design and execution methodology to deliver exceptional improvements in LNG production, greenhouse gas (GHG) emissions reduction and plant operability, while minimizing total project costs and the impact on day-to-day operations. As is often the case, the successful deployment of MPC technology delivered numerous less tangible—but no less important—benefits (e.g., improved process understanding among operations staff) and will enable further optimization advances in other areas of the plant in future years. This article will discuss some highlights of this MPC project.

QGC process description. QGC Pty. Ltd., a wholly owned subsidiary of Shell Plc., operates the QCLNG facility at Curtis Island near Gladstone, Australia. QCLNG operates two ConocoPhillips optimized cascade process (OCP) trains (**FIG. 1**) with an LNG production capacity of 8.5 MMtpy. The LNG plant is the first coal seam gas (CSG)-to-LNG facility in the world.

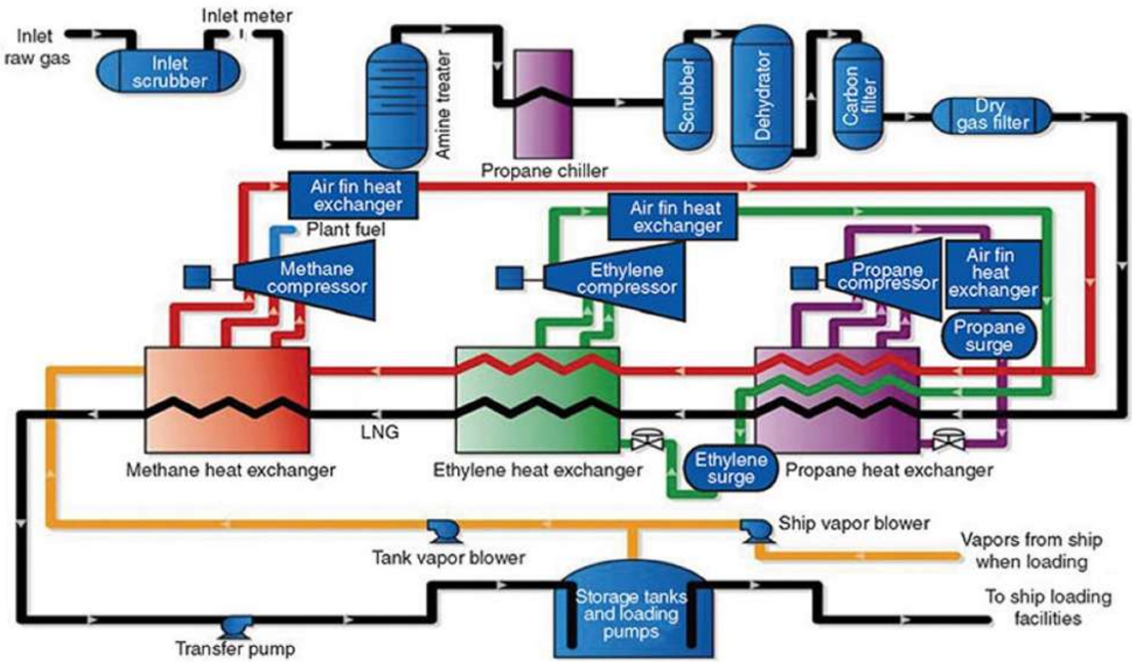

FIG. 1. OCP process flow diagram.

CSG is a form of naturally occurring gas extracted from coal seams. Natural gas from coal seams formed 200 MM yrs–280 MM yrs ago (at the same time coal was formed) from prehistoric organic deposits. This gas is trapped in the tiny cracks between the coal seams and groundwater under pressure. When the water is released, gas flows from the seams. Traditionally a risk for coal miners, these natural gas deposits are now being harnessed to support the growing LNG market.

The OCP process can be broken down to four principal areas: inlet receiving, gas treatment, liquefaction and LNG storage/loading. Liquefaction is performed in three stages of pure refrigerant cascade. The first cooldown of feed gas is via propane refrigeration, followed by ethylene and final cooldown by methane refrigeration. The propane circuit also cools down the ethylene and methane streams, while the ethylene circuit cools down the methane stream as well as the feed gas. The process is highly heat integrated, hence its extremely high thermal efficiency. Boiled off-gas (BOG) from the LNG tanks is returned to the trains to be recompressed by the methane compressor.

All propane, ethylene and methane compressors are driven by variable-speed gas turbines, and heat from the process is rejected to the atmosphere by fin fan cooling. Therefore, the plant's operating conditions are heavily influenced by ambient air temperature, humidity and wind direction/speed. To maximize LNG production, the refrigeration compressor's gas turbines must be kept fully loaded while observing process and equipment constraints at varying ambient temperatures. Once the gas turbines are fully loaded (generally operating on exhaust gas temperature limit), further feed gas increases will reduce turbine speed and increase the process pressure and temperature, pushing closer to plant operating envelope constraints. To maximize thermal efficiency and LNG production, the three refrigeration loops must be optimally balanced to ensure operation at the ultimate constraint of the operating envelope with minimum fuel gas usage. To achieve this, various process handles are available, each with unique effects on net fuel gas usage.

Project objectives. The project objectives were to:

- Review historical plant performance and gain a deep understanding of process limitations, regulatory control performance and process giveaway.
- Thoroughly model the process through a comprehensive automated step test.
- Deploy an MPC application that will:
  - Improve plant stability and resilience to load disturbances, such as trips to the adjacent train and changes in ambient temperature or wind direction/speed
  - Improve plant throughput when not limited by refrigeration or feed gas capacity
  - Improve plant thermal efficiency by reducing net fuel gas consumption per unit of feed gas.

Each project objective was achieved, and further details are discussed in the following sections.

TECHNICAL CHALLENGES

Base layer regulatory control inadequacy and poor disturbance rejection. A regular requirement when implementing MPC technology is that the base layer regulatory controls are designed and tuned to provide good servo response and disturbance rejection, while facilitating linear MPC models and minimal settling times. In this application, due to the highly interactive nature of the liquefaction mainline flow control problem, the decision was made to have the MPC modulate mainline control valve outputs directly. This unusual design choice was made feasible by the MPC software's[a] ability to support intermediate variables (IVs) with feedback at a 15-sec execution frequency. The result is a more resilient basis for the application's lower frequency control and optimization objectives.

FIG. 2 shows the simplified process flow diagram outlining the train's feed pressure and flow variables. Pressure control PC-2 is designed to maintain stable feed gas pressure to the train. Flow control FC-1 utilizes flow measurement from the metering package upstream of the feed gas heater, and a flow control valve located downstream of the high-stage ethylene feed chiller. Accurate train feed flow is a fundamental control requirement on an OCP LNG train: during changing ambient conditions or transient temperature swings (which can occur when hot effluent air is blown into the turbine intakes on the adjacent train), the train flowrates must be quickly reduced to avoid an excursion outside the desired plant operating envelope.

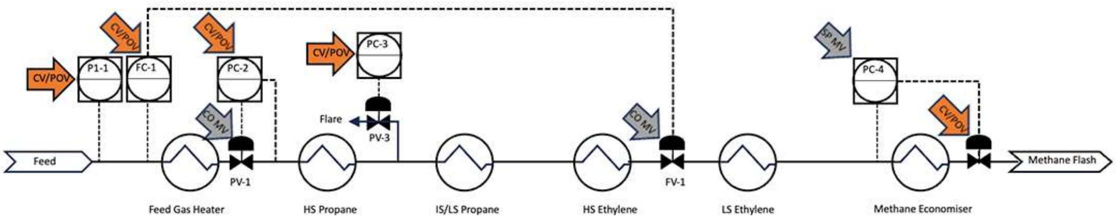

FIG. 2. Pressure and flow variables.

Challenges to the base layer control strategy are clear: front-end pressure PV-1 impacts train flow through FC-1, and flow will also impact pressure at PC-1. An additional semi-independent variable is the pipeline pressure PI-1, which can vary widely based on the throughput of the plant and the production rates of the upstream facilities.

Plant modeling revealed the fundamental relationships between PI-1 and PV-2/PI-2 and PV-2/FC-1 models. These relationships were included in the software's[a] application using the non-linear model feature; combined with PC-4 that is included in the control strategy to dynamically assist during transients, the application provides accurate pressure and flow control at all pipeline pressures using all three mainline control valves. Following commissioning, the pressure and flow pulse resulting from a trip of the opposite train would be absorbed on the surviving train, with far less process deviation than was previously capable in either operator/distributed control system (DCS) control.

Non-linear turbine variables. Another design challenge for this application was the requirement to cater for three turbine resident suction pressure controls which, depending upon the process operating point, can either be on-control and directly modulating turbine speed, or off-control, where an underlying turbine control system constraint has capped turbine capacity. The application process model has been designed so that the MPC will seamlessly optimize suction pressure while the turbine suction pressure master control setpoints are on-control and then utilize other manipulated variables (MVs) when the suction pressure master control setpoints are off-control. This exploits the full capacity of the turbines while observing important process constraints without the need for development of many unique models and/or complex model or variable-switching logic.

The OCP process utilizes three refrigerant circuits to liquefy the natural gas feedstock with each service comprising twin compressors in parallel—generally, both turbine/compressor sets are online. The turbine controls are resident in turbine control systems supplied by the turbine vendor, with an external master suction pressure control setpoint for turbine load control. During low production or low ambient conditions, the turbine suction pressure controls are on-control, meaning each suction pressure setpoint MV will have direct process response to its respective turbine and process-related controlled variables (CVs).

During higher ambient or production conditions, a turbine override will become active—this is generally the turbine combustion temperature (also known as the T48 temperature). **Note:** Each refrigerant turbine will have a unique T48 temperature, and it is only when both turbines in a service are T48 limited that the master suction pressure is genuinely off-control. At this point, each turbine T48 temperature remains clamped at the override setpoint programmed in the turbine control system. This process discontinuity is a challenge for linear MPC applications, as the variable is no longer continuous (i.e., there is no measure of the T48 'error' or deviation above the turbine capacity constraint and the process relationship between the suction pressure MV and respective process-related CVs are no longer present).

To address this situation, the MPC utilizes a calculation of the T48 temperature extended by a scaled measure of the suction pressure deviation above the suction pressure MV setpoint. **FIG. 3** illustrates how the extended T48 temperature is calculated to create a linear and continuous variable (highlighted in yellow). This is an MPC design technique that ensures turbine load can be optimized to exploit the full available capacity that is defined by the extended constraints (avoiding the need to give up on some compressor capacity to maintain some CV 'error' or movement beyond the MPC constraint limit).

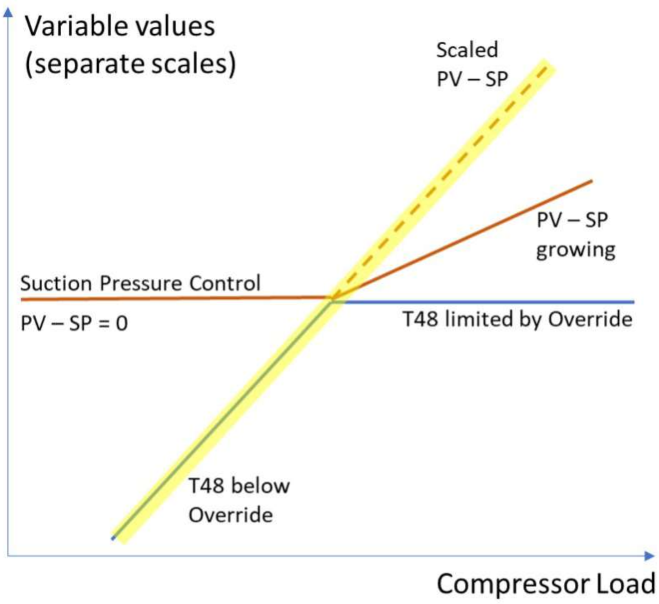

FIG. 3. Extended turbine constraint calculations.

As the suction pressure setpoints are MVs, the MPC model must remain accurate when the suction pressure MV is off-control and no longer affects the various constraints as it would in the on-control state. The application process model has been designed so the MPC will seamlessly optimize suction pressure MVs while the turbine suction pressures are on-control, and then utilize other MVs to control the process constraints when the suction pressure MVs are off-control.

Modeling the highly heat integrated process. The software[a] uses a flexible model environment whereby IVs may be modeled and included in the control relationship between MV and ultimate CV. IVs with constraints become standard CVs—however, not all IVs have defined constraints. The final application model is a convolution of models from MVs through to ultimate CVs. Advantages of this approach are that individual sub-models are often more easily identified if the inputs and outputs are closely related with relatively short dynamics. The control advantage from the perspective of the MPC is that base layer control action and disturbance rejection are handled by the IV prediction, thereby reducing unnecessary and/or late MPC MV movement. This approach will also naturally resolve some matrix conditioning issues that can arise with near parallel CV relationships.

The software's[a] automated step test feature was used to provide a detailed and complete process model, including many subtle relationships such as those between each refrigerant suction pressure MV and alternate turbine constraints and fuel gas flow, as well as between most MVs to fuel gas flow.

Train Flow IV is the primary control handle for the methane high-stage flash vessel pressure, which is often an active constraint during high ambient temperature conditions. Using Train Flow IV and turbine suction pressure MVs, an accurate process observation for this constraint is obtained. The high-stage pressure IV is then used to provide an accurate estimate for the methane low-stage flash vessel pressure, a constraint that is also regularly active during LNG ship loading.

The final piece of the liquefaction sub-model is an estimation of "net LNG," derived from train flow, methane low-stage flash vessel pressure and the sum of turbine fuel gas IVs. Based on this estimation, a single optimization objective to "maximize net LNG" directs the application to seamlessly cater to the two distinct plant modes: (1) when the plant's throughput is limited by upstream pipeline pressure and fuel gas efficiency is the focus; and (2) when the plant is limited by refrigeration capacity and maximum production is prioritized. The focus on model consistency (gain ratio accuracy) helps to overcome typical plant behavior, such as unequal turbine capacities on each train—one single process model derived from step testing only one train has been successfully applied to both trains, managing turbine sets of distinctly different capacities.

BUSINESS IMPACTS

Tangible results. The commissioned MPC applications have delivered substantial tangible LNG train process efficiency, environmental, economic and operational benefits, which are estimated to have delivered a project payback of less than one week. Factors that contribute to this benefit calculation include:

- Reduced GHG emissions by minimizing refrigeration power used per amount of LNG produced in the tanks, unlocking significant environmental benefits.
- Increased LNG production by maximizing LNG in the tanks per incremental unit of feedstock consumed by refrigeration power by consistently operating close to the operating envelope constraints.
- Operating envelope and process safety compliance have dramatically improved: examples of the reduction in process variance are shown in **FIG. 4.**
- Increased process stability by fast rejection of external disturbances through coordination of multiple process handles unloading operational workload has enabled further environmental and economic benefits to be realized over time.

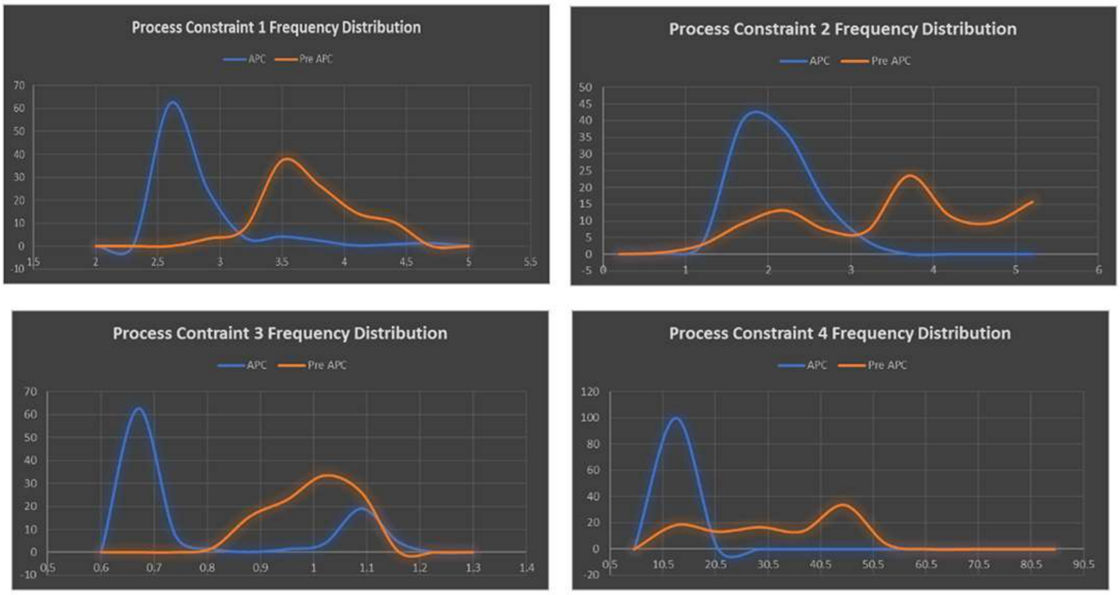

FIG. 4. Pre- and post-process histograms data showing significant reduction in process variance, and the shift in operating point towards the envelope limit.

Non-tangible results. While the tangible results listed above demonstrate a quantum shift in operational performance, the non-tangible benefits delivered by this project are equally important. These factors include:

- A knowledge increase in operational and engineering personnel in terms of process understanding, equipment limits and process performance. This stemmed from multi-disciplinary design discussions followed by a thorough plant step test. When combined with operational experience, the MPC reveals aspects of the process that were previously not well understood. Continuing investigation and analysis open the possibility of further optimization opportunities that were not previously feasible.
- Despite the extremely short payback period of the project, minimizing total project cost is critical as it can be a prohibitive factor for investment in MPC projects. The cost includes the total MPC project cost as well as other indirect cost, such as smooth implementation and step tests with no operational upsets (no flaring, no production loss, minimal disruption to operational plan), and quick design and deployment to ensure early realization of MPC benefits. Utilizing the combination of

implementation strategy, technical expertise and innovative software tools, the project team delivered two complex MPC applications within 7 mos from design to final sign-off.

- A unique aspect of this project was the quick and determined focus on communicating project benefits thoroughly and promptly through the organization, which led to number of upsides:
    - The quick project execution ensured that very few other plant and equipment changes diluted the calculation of benefits. Accurate, clear and early benefits quantification provides the driving force within the business for excellent operational and process engineering acceptance and ownership, leading to high uptime of MPC applications, continuous growth in MPC benefits and future growth of MPC applications.
    - MPC benefits continue to grow since commissioning through regular MPC maintenance and tuning, as well as the relaxation of some operating envelope limits that has come with growing confidence in MPC performance.
- Despite typical large value creation by MPC, it also comes with high maintenance overhead. Industry experience shows that the complete loss of MPC benefits can happen within 6 mos–12 mos without maintenance. Reactive maintenance can support MPC benefits much longer but with diminishing value. Proactive maintenance will facilitate sustained—and in some cases progressively improved—MPC benefits. With the in-house MPC application knowledge that was developed through this project, and the simplistic approach to the application design with control and optimization performed purely based on a single process model (despite the complex nature of the control and optimization problem), proactive maintenance is being performed on the MPC applications to ensure these benefits are sustained for years to come. **GP&LNG**

ACKNOLEDGEMENTS

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NOTE

a. Yokogawa Electric Corp.'s Platform for Advanced Control and Estimation (PACE) advanced process control

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